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(6) A NEW CASUALITY CRITERION

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~~ABERDEEN PROVING GROUND, MARYLAND~~

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Gurney/hlh
Aberdeen Proving Ground, Md.

31 October 1944

A NEW CASUALTY CRITERION

Abstract

The passage of a small missile through a soft medium is compared with its passage through steel; and a point of view is adopted sufficiently wide to embrace the behavior of both media. Though surprise has often been expressed at the large cavitation produced in soft media, it is shown that this cavitation is to be expected, and of the observed magnitude. The results are applied to the experiments made to throw light on the wounding power of small fragments.

The 58 foot-pound criterion was originally put forward for application to bullets weighing an ounce or more. For very small fragments it is proposed that a new criterion could be founded on the size of the momentary cavity which they produce - the requirement being the formation of a cavity of diameter greater than a certain minimum. If m is the mass of the fragment and v its incident velocity, this leads to the relation mv^3 = constant. When the value of the constant is chosen to agree with the 50 milligram missiles used by Black, Burns, and Zuckerman, it is found that on extrapolating to greater masses, it leads to the requirement of 57 foot-pounds for a one ounce missile. Thus the criterion based on very small fragments is in sufficient agreement with the older criterion for larger masses.

Methods of applying this criterion to the estimation of casualties are discussed.

When a very small fragment is incident with a low velocity (say less than 300 feet per second), it will cause a casualty only if it happens to enter a very sensitive region, such as the eye. The total area of the body surface corresponding to these regions is so small that we make only a small error if we set the total area A equal to zero for these fragments, and regard them as ineffective. On the other hand, we shall be interested in all fragments for which A is not negligible.

In §74 of his handbook Cranz wrote "When a bullet penetrates into a soft body, like that of a horse or a man, an explosive effect is produced within the body". In the present war it has been found that extremely small fragments are capable of producing the effect of an internal explosion and of causing a wound which seems out of all proportion to the minute size of the fragments; various suggestions were made to account for this explosive effect. Although it is, at first sight, surprising, a little consideration shows that an effect of this order of magnitude is to be expected.

The passage of a small fragment through soft tissues is one example of the passage of a missile through a material medium. The class of solids includes substances of every degree of rigidity and hardness between jelly and steel. If we could obtain a general theory for all isotropic solids, it would apply to jelly at one end of the list, and to steel at the other end of the list. It would apply to missiles of all kinds, both projectiles and fragments.

The case which has received detailed treatment is the passage of an armor-piercing projectile through steel. In Robertsons's extension* of Bethe's theory the loss of energy by the projectile is divided into two parts: one part corresponds to work done in deforming the medium; the other part corresponds to the kinetic energy with which the medium moves aside, to allow the projectile to pass. The second term is proportional to the greatest cross-section of the projectile a and to the density of the medium ρ, since the mass set in motion (per unit length of path of the projectile) is proportional to the product of these two quantities. That portion of the medium which lies ahead of the projectile must move aside with a velocity less than, but comparable to, that of the projectile itself, v. Thus the kinetic energy transferred per unit length of path is

* NDRC Report No. A-16.

$$\frac{1}{2}\kappa\rho \quad av^2 \qquad (1)$$

where κ is not many times smaller than unity. These considerations are so general that they should apply to any missile in any medium.

Consider any plane P perpendicular to the track of the missile. When the greatest cross-section of the projectile reaches P, the medium is moving aside with the above kinetic energy, and continues to move until it is brought to rest by the restoring forces, due to the stretching of the material. The restoring forces then cause the motion to reverse its direction. The additional distance which the material moves radially before being brought momentarily to rest depends on the value of Young's modulus for the medium. When the medium is steel or other metal, the additional distance moved is doubtless, in most cases, a small fraction of a millimeter*.

Landolt and Bornstein's tables give the values of Young's modulus for steel, and for a gelatine gel, 20% gelatine and 80% water; the values are

steel	2.1×10^{10} dynes/cm^2	
20% gelatine gel	2×10^4 dynes/cm^2	(=ergs/cm^3)

From the definition of Young's modulus it appears that, for any missile passing through the gel, a large cavitation will be produced if the kinetic energy associated with the radial motion of the material is large compared with 2×10^4 ergs. Let us estimate then the kinetic energy due to the passage of a missile whose maximum cross section is only 10^{-2} cm^2. Taking the density of the gel to be unity, if it moves aside with only 660 feet per second (2×10^4 cm/sec), we have, per unit length of path of the missile

$$\frac{1}{2}\rho\ av^2 = \frac{1}{2} \cdot 10^{-2} \cdot 4 \times 10^8$$

$$= 2 \times 10^6 \text{ ergs.}$$

* See, however, BRL Report 489.

The enormous cavitation which has been observed for a sphere of 4×10^{-2} cm^2 cross-section, incident with a velocity of 2000 feet per second*, is thus to be expected. It is recognized that a small fragment passing through tissues with sufficient velocity produces damage at a considerable distance from its track. The investigation of cavitation was undertaken with a view to elucidating this effect.

It was stated above that we must take into account all fragments for which the value of A, the vulnerable area of the body, is not negligible. It is reasonable to suppose that for all fragments which produce a cavity of diameter greater than a certain limit d_o, the value of A is considerable. Now if we compare two fragments, of cross-section a_1 and a_2 respectively and incident with velocities v_1 and v_2, it appears from (1) that they will produce cavities of equal diameter if

$$a_2 v_2^{\;2} = a_1 v_1^{\;2}. \tag{2}$$

Thus, if $a_2/a_1 = (m_2/m_1)^{2/3}$ a possible criterion for casualty formation for small fragments would be founded on the requirement

$$mv^3 = \text{constant}, \tag{3}$$

the value of the constant being chosen to agree with experimental data, such as the cavitation experiments of Black, Burns and Zuckerman.

The earlier wounding criteria, dating from 1914 or before, were intended to apply to bullets weighing something in the neighbourhood of an ounce - that is, more than 400 times the mass of the missiles used in these experiments. The question arises whether a wounding criterion founded on (3), and conformable to the results of these experiments, would, if extrapolated to heavy fragments, be found to agree with the criterion which is in use for fragments in the neighbourhood of one ounce, namely the 58 foot-pound criterion. We shall show that this is the case, which is a strong confirmation of the validity of the previous argument.

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* Experiments by Black, Burns and Zuckerman, R.C. 264; and by Newton Harvey and McMillen (1944).

If the constant in (3) is chosen to correspond to a 50 milligram fragment incident with a velocity of 2000 f/s, that is, if we take

$$mv^3 = 4 \times 10^8, \qquad (4)$$

we find that for a one ounce fragment a velocity of 242 f/s is required; the number of foot-pounds of this ounce fragment is thus

$$\frac{1}{2}\,\frac{1}{32}\,\frac{1}{16}\,(242)^2 = 57 \text{ foot-pounds.} \qquad (5)$$

This result suggested that one could adopt a criterion based on very small fragments which would be in sufficient agreement with the criterion which is already in use for larger missiles*. Curves based on (4) and showing effective range against mass will be included in Ballistic Research Laboratory Report No. 493.

In the opening sentences of this report it was pointed out that some parts of the body surface are vulnerable to fragments of very small momentum, but that the sum of these areas is considerably less than the area which is vulnerable to more powerful fragments. A possible method of assessing the efficiency of a bursting projectile would then be to divide the effective fragments (at any distance from the burst) into two classes - those fragments for which the average total vulnerable area of a man is large, say, 4 square feet, and those fragments for which the total vulnerable area is small, say, 1.5 square feet. The latter class will include numerous additional fragments whose mass or whose velocity is too small to bring them into the former class. If the expected number of casualties were calculated in this way, with properly chosen criteria and vulnerable areas, the result should not be far from the truth.

At the present time, however, the ballistician will be satisfied with a less accurate procedure, and will prefer to use a single casualty criterion which avoids the necessity of dividing the effective fragments into two classes. The

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* According to Zuckerman, the depth of penetration into gelatin, etc., is proportional to $m^{1/3}v$; hence the suggested criteria founded on depth of penetration by Zuckerman and by H. Lamport lead likewise to an mv^3 law.

problem is to choose the criterion and the vulnerable area A in such a way that the calculated number of casualties agrees as closely as possible with the number which would be obtained if one took into account the fact that A does not really fall from a constant value to zero at a critical value of mv^3. If, for example, we take (4) as the measure of an effective fragment, the remaining problem is to choose the value of the vulnerable area A to accompany it. The required value doubtless lies between 2.5 square feet and 4 square feet, but there is great uncertainty on this point.

In conclusion it may be pointed out that there are two ballistic problems in which the casualty criterion is important; there is (a) the comparison between projectiles which already exist, and (b) the question whether it is desirable to design projectiles having finer fragmentation than those already in use. With regard to (a) it should be noticed that the average fragment size from most projectiles is more than one gram; consequently, little change in efficiency is to be expected by adopting a better criterion whose chief advantage is that it gives proper consideration to fragments of 100 milligrams and less. Hence if (4) is adopted, the results for these projectiles may differ little from those obtained from the 58 foot-pound criterion. From this, however, it must not be concluded that the same will be true if we discuss the efficiency of a new grenade or bomb having a finer fragmentation than those now in use. When the average fragment size is small, there may be a considerable difference between results obtained from the two criteria.

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